AD-A117 153 NAVAL OCEANOGRAPHIC OFFICE NSTL STATION MS F/G 17/6
AEROMAGNETIC DETECTION AND DEFINITION OF SEAMOUNTS.(U)
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NAVAL OCEANOGRAPHIC OFFICE TECHNICAL PUBLICATION

AEROMAGNETIC DETECTION AND DEFINITION OF SEAMOUNTS

Dewey R Bracey

JUNE 1982

PREPARED BY
COMMANDING OFFICER,
NAVAL OCEANOGRAPHIC OFFICE
NSTL STATION, BAY ST. LOUIS, MS 39522

PREPARED FOR
COMMANDER,
NAVAL OCEANOGRAPHY COMMAND
NSTL STATION, BAY ST. LOUIS, MS 39529

FOREWORD

The need for a rapid, economical method of seamount detection and definition as to size, shape and depth for subsequent bathymetric development has led to the investigation of geophysical methods as an initial means of detection and definition. This report develops an aeromagnetic seamount detection and definition method that can fulfill these requirements with existing survey platforms and equipment.

C. H. BASSETT
Captain, USN
Commanding Officer

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO. AD A117 155

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

Aeromagnetic Detection and Definition of Seamounts

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

Dewey R. Bracey

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Code 8230
U. S. Naval Oceanographic Office
Bay St. Louis, MS 39522

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

12. REPORT DATE

June 1982

13. NUMBER OF PAGES

23

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)

UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

SEAMOUNTS AEROMAGNETIC DETECTION

MAGNETIC ANOMALY DETECTION (MAD)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report develops an aeromagnetic seamount location and definition strategy using the observed anomaly characteristics and the observed relationship between the MAD electronic filter and seamount peak-depths. Limitations and recommended refinements and future development of the method are also discussed.

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S/N 0102- LF- 014- 6601

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INTRODUCTION

While it has been known for some time that seamounts have been located by detailed aeromagnetic surveys (see for example: Kontis and Young, 1965), no extensive surveys have ever been done specifically for this purpose. The following study attempts to define a simple, economical aeromagnetic seamount-detection strategy and a method of definition of the seamounts as to probable depth to peak and a rough outline of their basal dimensions.

I. BACKGROUND

Oceanic seamounts are generally composed of alkaline or tholeiitic basalt. The average intensity of magnetization (natural remnant magnetization) of 87 Pacific and Atlantic seamounts (Francheteau and others, 1970; Vacquier, 1972) is 0.0052 $\pm$ 0.0036 (standard deviation) emu/cm^3. This magnetization produces a concomitantly large associated magnetic total intensity anomaly.

An exception to this generalization has been found in the Tyrrhenian Sea, where two seamounts (Hadrian; Orosei) have been found with no apparent associated magnetic expression. It is believed that these seamounts are sedimentary (linestone?) continental fragments, separated from the nearby continental masses (Sardinia; Italy) in an earlier episode of sea-floor spreading.

These two examples, while certainly an exception to the generalization that all seamounts have associated magnetic anomalies, probably do not indicate that non-magnetic seamounts are a wide-spread phenomenon. It is doubtful that non-magnetic seamounts occur in the deep-ocean basins, being limited to certain marginal seas.

Despite the large magnetic anomaly associated with seamounts, and their similar intensities of magnetization, the magnetic data are usually not amenable to inverse model studies (determining the size and shape of the causative body from its magnetic field). This is due to the above mentioned large remnant magnetization vector associated with most seamounts, caused by (in most cases) the movement of the seamount from its place of origin to another location through the action of sea-floor spreading. In some cases, the northward component of this movement has amounted to 30° in latitude. The remnant magnetization may be 40-50 times larger (Vacquier, 1972) than the

induced magnetization produced by the earth's ambient field, whose contributions may be considered negligible in most cases. Since there is no way of determining what the direction of the remnant magnetization vector is from the total intensity data alone, the definition of physical bodies from the observed total intensity data is difficult if not impossible.

To illustrate this point, the known seamount topography from bathymetric surveys is often used together with various magnetization vectors to generate model magnetic fields by iterative methods that can be compared to the observed field from the same survey in order to determine the remnant magnetization direction (Vacquier, 1972). Such an application would hardly be useful if the object of investigation is the size and shape of the seamount itself as it is here.

The magnetic field of a seamount may also be influenced by later magmatic activity in which subsequent lava flows cool through the Curie temperature at times and/or places where the ambient magnetic field vector is in a different direction from that of the original basalt pile (Vogt, 1969), resulting in a reorientation of the resultant of the two magnetization vectors.

In summary, there is no "characteristic" seamount magnetic anomaly. The anomaly pattern is certainly dependent on the size, shape, and magnetization of the seamount; but a major controlling factor is the past history of the seamount.

It is apparent that detailed (line spacing close enough to allow detailed contouring) magnetic total intensity surveys yield data that are of somewhat limited value in attempting to define the causative body. A possible application of such data would be depth determination by the slope method (for example: Nettleton, 1971) _if_ the steepest gradient of the asso-

ciated anomaly were crossed by a track at the proper angle (90°), but this is problematical, depending on the orientation of the anomaly which is unknown at the time of the survey. Of course, a profile across the steepest gradient can be constructed from the contour data, but this involves certain assumptions that may not be warranted. A simpler, more economical method for depth determination as well as a qualitative method of determining seamount basal dimensions will be developed in a later section.

II. SEAMOUNT DETECTION

A careful examination of bathymetrically defined seamounts in the Atlantic, Pacific, and Mediterranean for which detailed magnetic total intensity data are available reveals that the area extent of detectable magnetic anomaly amplitudes ($\pm$ 200 nt) at normal flight altitudes (150-300 m) generally equals or exceeds the areal extent of the seamount. Therefore, the track spacings prescribed by Bracey (1981A) for seamount encounter at the required probability level would also be the optimum spacings for aeromagnetic survey detection. Obviously, the larger seamounts in relatively close proximity to the surface are the more easily detected due to the inverse cube relationship of magnetic field intensity to distance from source. The reservations and adjustments noted by Bracey (1981A) as to the "background noise" also apply. If the survey tracks are run in the prescribed direction (parallel to the seafloor spreading anomalies), this noise will be minimized. It should only present a problem near the spreading-ridge axis (within approximagely 200 nautical miles of the axis); in areas of extremely rough sea-floor of relatively high relief; and in crossing of transform faults, where a positive magnetic anomaly may abut a negative anomaly (or vice versa) across the fracture. In the case of known transforms, track crossings may be anticipated from pre-flight planning. For unknown transforms, the appearance of adjacent anomalies on several subsequent tracks will serve to define the feature as a fault.

As an independent means of seamount detection, one that would be particularly valuable in the case of any non-magnetic seamount encountered, the use of an airborne gravimeter should be considered. Initial tests aboard the Project MAGNET aircraft indicate that airborne gravimetry may be feasible, although further testing is necessary. A possible difficulty may result from the problem of obtaining useful data on certain headings (N-S) due to Eötvös

effects. Since a majority of the oceanic magnetic lineations lie in a general N-S direction, flying at some other azimuth to benefit the gravity measurements may adversely affect the magnetic measurements. Also, the present restrictions on heading changes during gravity surveys places severe limitations on the ability to maintain a preestablished track pattern.

If real-time detection capability is desired, installation of an x-y plotter aboard the aircraft to plot aircraft track and residual magnetic anomaly profiles will probably be required. With this capability, the party-chief should be able to pinpoint seamount locations, fly "splits" if required, and determine the alignment of definition profiles (explained in the following section) to provide depth-to-source information.

If there is no real-time requirement, residual profiles can be plotted along track in the office using existing procedures, probable seamount locations noted, and definition track alignments determined for later flights.

If the object of the survey is twofold, that is, delineation of the local sea-floor spreading anomalies as well as seamount detection, the proper track orientation for the former is normal to anomaly strike. This will certainly present problems in separating seamount anomalies from spreading anomalies, but it may be possible.

Blakely and others (1973) described a method whereby magnetic sea-floor spreading anomalies, which are essentially two-dimensional sources, may be separated from three-dimensional sources (seamounts, fracture zones, etc.) caused by local topographic relief by using component data from a vector magnetometer. The required component is the horizontal field (H), combined with the declination (D). These data are then used to compute the anomalous magnetic field in the direction of anomaly strike: $Y_a = H_a \text{Cos}(S-D)$, where S equals the angle of anomaly strike. If the source is in fact two-dimensional,

this field value should be zero. If it is some value other than zero, the source is probably three-dimensional; and a bathymetric feature is implied. An example of this application to sea-floor spreading anomalies in the Western Pacific is shown in figure 1.

The Project MAGNET aircraft is uniquely suited to this application, having a vector magnetometer already installed. The remaining problem would be the development of a simple computer program to compute H_a and Y_a using the S value obtained from examination of the anomalous total intensity profiles obtained simultaneously in the survey area.

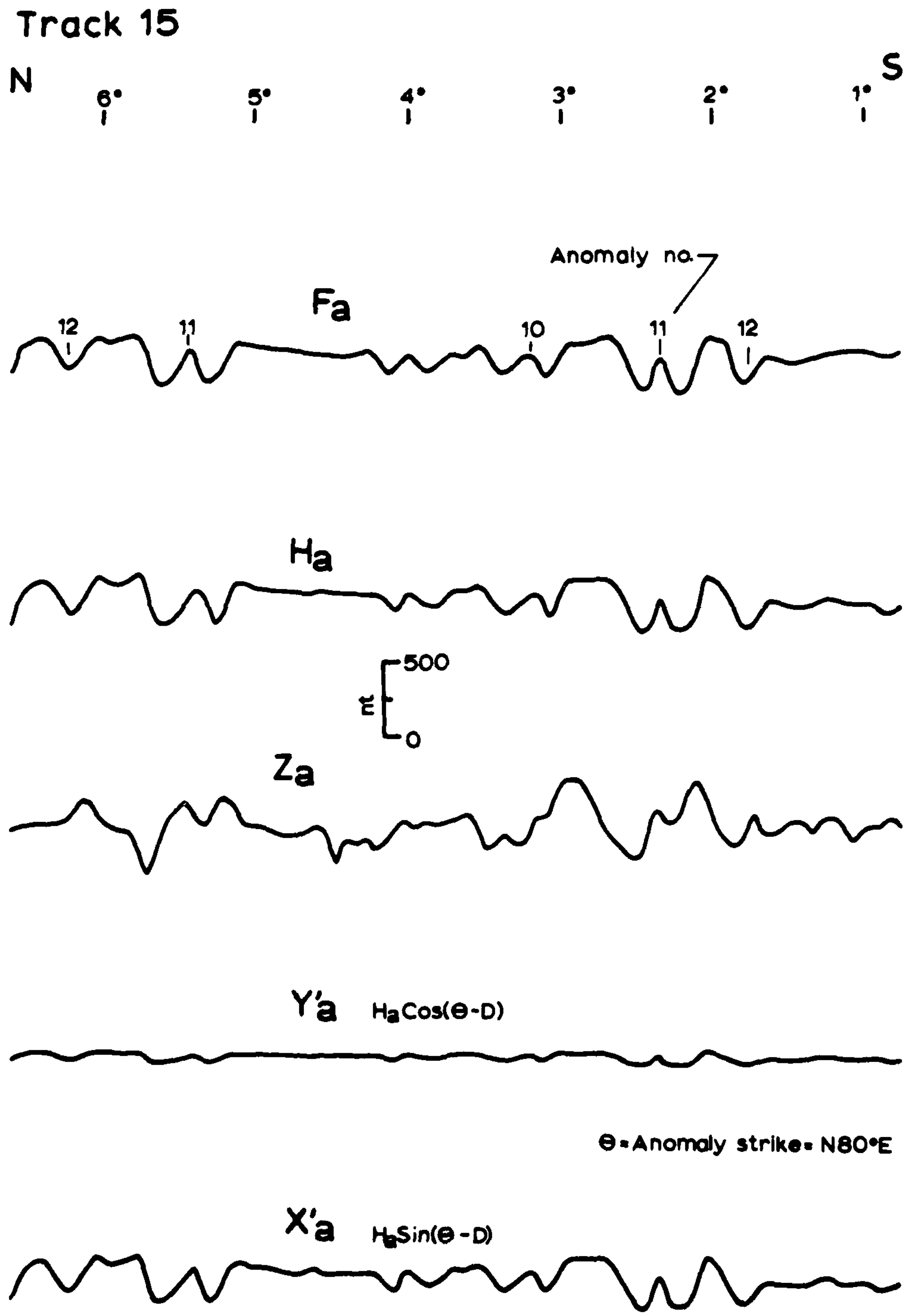

Figure 1. Example of magnetic component data over two-dimensional sea-floor spreading anomalies (from Bracey, 1981B).

III. SEAMOUNT DEFINITION

The term "seamount definition" as used here refers to the depth to the top of a seamount (seamount peak) and the general outline of its base. This is the most difficult part of any geophysical seamount-delineation stratagem.

A. Seamount Peak-Depth Determination

As noted above, magnetic depth determinations by the slope methods or the more sophisticated mathematical methods require a profile that passes over the steepest part of the magnetic anomaly slope (usually over the seamount peak). This, in turn, will usually require a rather detailed magnetic survey, resulting in a magnetic contour chart, before the proper location of this profile can be determined. Even with this preparation, depth estimates to the top of the magnetic source may be in error by as much as 10%-15%.

As alternative depth determination method has been devised using the amplitude output of the Magnetic Anomaly Detection (MAD) electronic filter (.08-.6 hz) presently used in conjunction with the ASQ-81 metastable helium magnetometer on ASW aircraft and the digital filter amplitudes from marine magnetic data using the same bandpass.

It was found on examination of filter-output amplitude data collected over seamounts that there seemed to be a direct relationship between maximum peak-to-trough amplitudes and seamount peak-depth. While this physical relationship seems intuitively reasonable, the mathematical expression of this relationship awaits further investigation.

Figure 2 shows the results of the comparison of filter-output amplitudes to seamount peak-depths for 23 seamounts in the Atlantic, Pacific and Mediterranean. Data from both electronic (open circles) and digital (filled circles) filters of the above noted bandpass have been used in the comparison. It should be noted that the track orientations of these

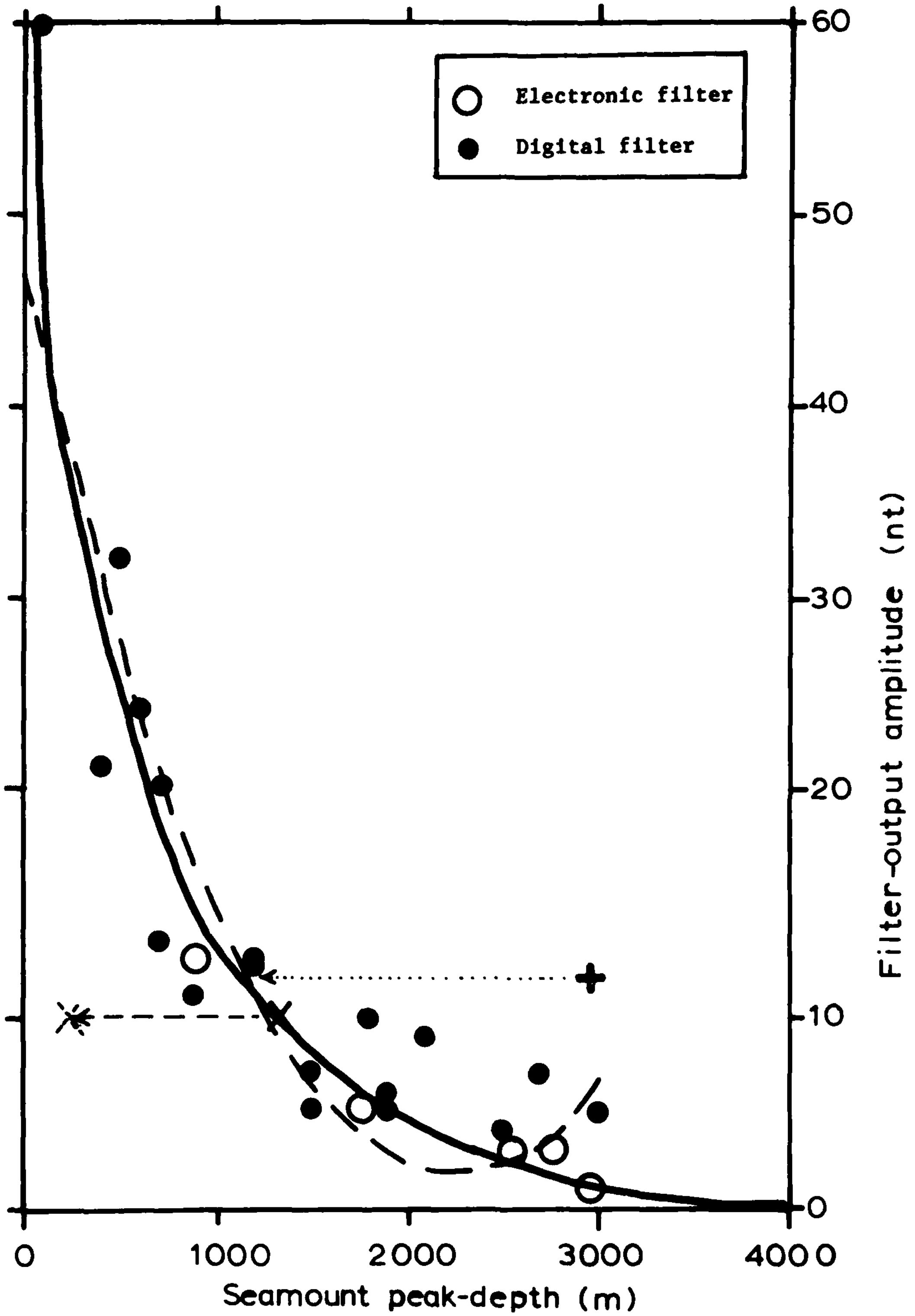

Figure 2. Seamount peak-depths plotted as a function of filter-output amplitude. Data fitted with 2nd-degree polynomial (dashed curve) and approximation(solid curve) that best fits the observed data. "X" and "+" values are used as examples in text and have not been included in the computations.

data are not necessarily in the ideal direction for maximum amplitude detection (see below). Only data for peaks $\leq$ 3000 m were used in the study as at depths greater than this, the low filter-output amplitudes approach the background noise level of the filter.

A limiting factor in this study is the possibility of excessive amplitudes in the digital (marine) data resulting from "noise" caused by the hand digitization method formerly used to process the marine total intensity data. This error source is difficult to evaluate but should eventually be eliminated by the acquisition of high-quality digital data.

Another limiting factor is the fact that the electronic filter is usually set on a maximum 10 nt deflection. This limits output amplitudes to approximately 13 nt, and amplitude data for those seamounts with peaks in the range 0 to -1000 m was not available. As can be seem from figure 2, additional data in this depth range would certainly improve the veracity of the derived curve fits.

As shown in figure 2, the data were first fitted with a second-degree regression curve (dashed line) which produced a fairly good fit (R=79%) except that at the high and low ends of the scale there are obvious unrealistic excursions. A second curve (solid line) that resembles an exponential function (probably a more reasonable expression of the data distribution) was devised to more closely fit the data points. The maximum deviation of the data points from this curve at the shallow (< 1000 m) end of the scale is 300 m. Deviations at greater depths are considerably more, probably resulting from excessive noise-induced amplitudes in the digital marine filter data as discussed above.

Implicit in these empirical data are the following factors: (1) seamounts have essentially equivalent magnitudes of magnetization, and

(2) seamount magnetic anomalies have essentially the same frequency content, at least within the limits of the band-pass used here. As to factor (1), while the magnetization data of Section I (0.0052 $\pm$ 0.0036 emu/cm^3) indicates a large magnitude of seamount magnetization, the variation is also quite large although less than an order of magnitude. In view of the fact that the orientation of the magnetization vector of most seamounts is quite variable, this fact is not surprising. What is surprising is that according to the admittedly limited empirical data, this variation in magnitude has little effect on the filter-output amplitudes. This curious fact requires further study.

The second factor (similarity of frequency content of seamount magnetic anomalies) can be investigated using fourier analysis of magnetic anomaly data collected over seamounts. This data is already quite voluminous, and the only requirements are time and expertise.

Until these studies can be carried out, and unless there are other serious objections that have not been considered in this study, there would appear to be no reason why the empirical results obtained here cannot be applied. Further magnetic data collection and depth verification can of course be used to refine the curve derived from the empirical data, and survey effort can continue. The rationale being--if it works, use it until something better comes along.

Other conclusions drawn from this study, again limited by the available data, are that the angle of incidence of the survey track with the magnetic anomaly gradient associated with a seamount is not particularly critical. Unlike the data required for slope-depth determinations (normal to the gradient), there appears to be less than a 10% change in filter-output amplitude on headings within $\pm$ 60° of gradient-normal. There also appears to be little affect on amplitude if the survey track does not pass directly

over the magnetic maximum or minimum. Tracks within about one nautical mile of these peaks seem to produce similar amplitudes.

In addition to the obvious advantage of a direct method of determining seamount peak-depths, the filter-output amplitude method would also provide important economic advantages: (1) it can be done with existing, already installed equipment; and (2) the method requires only two or three definition flights over (or near) the maximum gradient of the associated magnetic anomaly (direction and location of flights to be determined by inspection of the data obtained through the methods of Section II), as opposed to the detailed survey pattern required for other depth determination methods. The savings in flight time should be substantial.

B. Seamount Basal-Dimension Determination

Basal dimension determination is, in one sense, the easiest part of seamount definition and, in another sense, the most difficult. This determination is, of necessity, qualitative and requires a thorough knowledge of the possible magnetic anomaly patterns to be expected from seamounts of various sizes, shapes, and geographic locations. This knowledge can only be acquired from extensive observation of large numbers of seamounts and their associated magnetic anomalies.

The method consists of outlining the plan view of the seamount base from the observed characteristics and lateral extent of the associated magnetic anomaly. While there may be considerable variation of the resultant plan from that of the actual seamount, results are generally of sufficient accuracy to guide the prospective bathymetric surveyor (the ultimate definer) to seamount encounter. This plan information, together with the location of the seamount peak(s), should allow the bathymetrist to plan and execute an accurate bathymetric survey.

Obviously, this phase of the seamount definition will require an experienced geophysicist. The additional experience gained in repeated applications of the method to seamounts in various locales will certainly improve accuracy.

IV. LIMITATIONS

One of the more obvious limitations to this, or any other, magnetic depth determination method is that the depth determined is the depth to the top of the magnetic source material which is not necessarily the depth to the top of (in this case) the seamount. The seamount may have an unknown thickness of sediment (including corals) on its crest. This sediment thickness is dependent on numerous variables some of the more important being age, latitude, depth, and the paleo-dynamics of the seamount.

Unfortunately, information on these and other important factors (paleo-lysoclines, sedimentary hiatuses, etc.) will usually not be known to the surveyor. One is therefore faced with the problem of devising some reasonable and practical method of estimating probable sediment thicknesses for vast oceanic areas with extremely limited data.

Such an effort is illustrated by figure 3 where sedimentation rates (exclusive of those deposited through the action of turbidity processes) from various sources are plotted as a function of latitude, which is probably the single most influential variable. The tentative connection between this graph and conditions in real-life cannot be over-emphasized, but it is believed that it has some link with reality and may help to give rough approximations for "worst case" thickness computations. "Worst case" is here defined as an over-estimation of sediment thickness. As more comparative data (bathymetric depths versus measured magnetic depths) and other pertinent data are acquired, the curves may be refined.

The two curves represent sediment deposition above and below the present lysocline found at depths of 3700-4000 m (Berger, 1968), below which calcium solution increases rapidly down to the calcite compensation depth, below which solution equals supply. There is also some solution above the

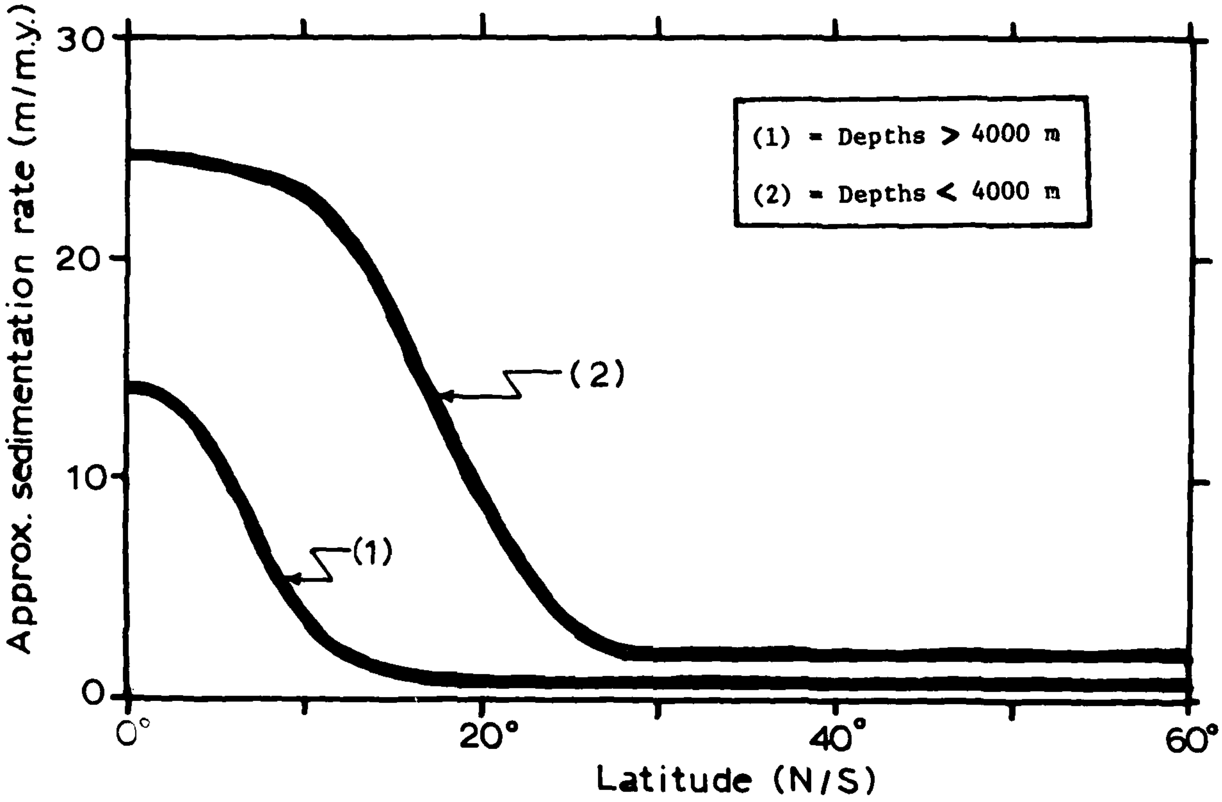

Figure 3. Sediment accumulation rates as a function of latitude.

lysocline to within about 200 m of the surface, but it is less rapid (Van Andel and others, 1975). Note that the curves are lobate, indicating the high equatorial calcium carbonate production rate, falling off rapidly to the 1 - 2m/m.y. rate found presently at higher latitudes (Van Andel and others, 1975).

An example of the use of these curves is given for a seamount at low latitude (16.5°N) in the South China Sea. The maximum amplitude of the filter-output for a track flown over this seamount was 10 nt, which plots at the 1300 meter depth (X on figure 2). Suspecting considerable coral growth in this area, we first use the $\angle$ 4000 m curve in figure to determine sedimentation rate ($\sim$ 14m/m.y). From the scientific literature (Ben-Avraham, 1978), we find that the approximate age of the South China Sea-floor is 70 m.y. The seamount cannot be older than the sea-floor, although it may be younger. We would then predict that a maximum of about 1000 m of sediment (70 X 14) may be expected on this seamount. Our corrected peak-depth is then 300 m (1300-1000 m). Actual charted depth of this feature is 200 m (indicated by dashed arrow on figure 2) so that in this example our final error is 80 m, an order of magnitude improvement over the original error of 1080 m.

Again, the over-simplification represented by figure 3 of extremely complicated phenomena is emphasized. However, the necessity for guidance on this possible error source by the geophysical surveyor makes such an attempt necessary, particularly in low-latitude areas with high calcium precipitation. Hopefully, the curves will increase the "safety factor" by an under-estimation of seamount peak depths.

Another problem encountered in this study was the apparent "magnification" of filter-output amplitudes over milti-peaked seamounts. This problem is illustrated by the "+" value shown on figure 2. These values were obtained over a charted multi-peaked seamount in the New England Seamount Chain. Note

that this value is much higher than those of the other empirical data for seamounts at these depths (shown by dotted arrow). The net effect of the higher amplitude readings is to make the seamount peaks appear shoaler than they really are. As a safety factor, this is preferable to having them appear deeper.

It has been suggested that this "additive" effect could be reduced or eliminated by using a narrower band-pass filter. For example the "No. 1" filter developed by NORDA and already installed in the Project MAGNET aircraft. This possibility will be investigated.

Another hardware-related problem involves the noise spikes or "ramp functions" engendered in the filter-output in areas of steep magnetic gradient. This noise makes the filter-output analog trace extremely difficult to interpret. A possible solution is the use of a digital filter (existing or of new design) operating on the magnetic intensity data.

V. CONCLUSIONS

There would seem to be no cogent reason why the aeromagnetic seamount detection and definition methods described above cannot be immediately applied. The definition limitations outlined in the preceding section will generally lead to an under-estimation of peak-depths and, therefore, have a "built-in" safety factor. These limitations may be minimized or eliminated by methods described in the succeeding section.

VI. RECOMMENDATIONS

Recommendations for further refinement/development are listed in order of priority:

(1) In order to accumulate more empirical data, field parties should be instructed to make at least one pass over seamount magnetic anomalies encountered during low-level survey operations with filter gain set at the highest level. The track should be oriented in a N-S direction (the usual direction for maximum gradient encounter); or if the gradient varies significantly from this orientation, the correct course may be selected by the observer.

(2) Maintain a plot, similar to figure 2, of NORDA filter No. 1 output amplitudes over seamounts encountered in survey operations.

(3) Fourier analysis of magnetic anomaly data collected over seamounts with the object of designing a digital filter specifically for the purpose of defining peak-depths.

(4) Test flights over charted (bathymetrically and magnetically) single peaked seamounts to test the effect of altitude, track orientation relative to gradient, and reciprocal headings on filter-output amplitudes.

(5) Concern has been expressed as to the effect of low dip-angles of the ambient magnetic field on amplitude. Test flights should be flown over recent (to reduce the effect of any sediment cover) seamounts at low magnetic latitudes. These flights could be conducted during transit to other survey locations.

(6) Further testing of airborne gravity should be instituted, perhaps in conjunction with (4) above, to determine the applicability of this data to seamount detection.

(7) Investigation of alternative methods of seamount definition (vertical gradiometer, multi-axial cryogenic magnetometer, etc.) should be instituted.

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